SUPPORT OF VISITING SEISMOLOGISTS

John T. Kuo

Lamont Geological Observatory
Columbia University
Palisades, New York

Grant No. AF-AFOSR 62-30

Project No. 8652

Final Report

Period Covered: 1 March 1962 - 31 August 1965

1 September 1965

Prepared for

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
OFFICE OF AEROSPACE RESEARCH
UNITED STATES AIR FORCE
WASHINGTON, D. C.

WORK SPONSORED BY ADVANCED RESEARCH PROJECTS AGENCY

PROJECT VELA-UNIFORM

ARPA Order No. 292-62

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ABSTRACT

During the past three years, nine visiting seismologists from Japan, England and Denmark have participated in a program of research at Lamont. During their stay here, they worked either jointly with the Lamont seismology staff or individually on many important problems, some of which directly bear on the detection of explosions and earthquakes and some of which are fundamental enough to offer wide application to the basic understanding of the properties of the earth's crust, the mantle and the core, and the earth as a whole.

As a result of their research, we have made progress in earthquake prediction--considering earthquakes as statistical events in a stochastic process; we have a more detailed understanding of the travel times of body waves through North America for both nuclear explosions and earthquakes; we have extended the theoretical investigation of wave propagation through complicated structures, such as a corrugated interface and a medium with a hyperbolic type of interface; and we have a detailed understanding of the dissipation factor 1/Q both in the upper and the lower mantle and in the core. These findings are closely related to the problems of location of seismic events and of differentiation of explosions from earthquakes.

INTRODUCTION

The objective of this grant, entitled "Support of Visiting Seismologists," was to provide the exchange of scientific knowledge and experience in the field of seismology between the visiting seismologists and our seismology staff. During the past decade or so the Lamont Geological Observatory of Columbia University has made significant contributions in the field of seismology, particularly in the intensive study of surface wave propagation in the earth. As a result of its international reputation in this well established branch of the Lamont activities, and because of its many facilities and large seismogram library available for use in research projects, it was felt that eminent scientists from other countries would come to Lamont to engage in research which would be of significance both to Project Vela-Uniform and to the field of seismology in general.

Under this program, nine distinguished seismologists, including such world-renowned seismologists as Sir Harold Jeffreys and Dr. Inge Lehmann, have participated in this program. These scientists have profited by the fact that Lamont is staffed with not only a group of seismologists with a wide variety of research interest and experience but also other scientists with diversified interests in virtually all branches of earth sciences and oceanography. In turn, they have contributed immeasurably to the breadth and maturity of our staff at Lamont through a give-and-take close communication. Their accomplishments are summarized in the following parts of this report.

ACCOMPLISHMENTS

Lomnitz has made considerable strides in the study of earthquake prediction. He considered earthquakes as statistical events in a stochastic process, which is described as a semi-Markov type in three variables: space, magnitude and time. For all earthquakes with magnitudes greater than 6 1/2 in the years 1904-1952, as published in Gutenberg and Richter's Seismicity, he has mapped the distribution of mean annual energy release per square kilometer for every

square degree of the earth's surface. A series of seismicity maps for every major seismic region and for the earth as a whole were obtained. He has found that the time intervals between shocks above magnitude 6 1/2 were distributed according to the lognormal law and were tested by the Chi-square method. A theoretical mechanism for the generation of a lognormal distribution of earthquakes was also suggested. On the basis of the worldwide data of earthquakes for 1904-1952, it was found that the stochastic model agrees with earthquake processes.

Asano has investigated both the cases of normal and oblique incidences of P and SV waves on a corrugated interface. The reflection and refraction coefficients of elastic waves impinging on such an interface for various angles of incidence can now be calculated theoretically. Along this general direction of the effect of sloping interface on surface wave propagation, Takahashi has investigated the Love wave propagation in a layer overlying a half space, where the layer thickness varies hyperbolically as shown in figure 1. For the hyper-

Figure 1

bolic type of interface, the wave equations are separable. One of the important findings was that for the first approximation the phase velocity of Love waves at a given point of observation in a layered medium with linear variation in layer thickness was found to be the appropriate phase velocity for the case of a parallel layer with the corresponding depth at the given point, independent of the direction of wave propagation. A similar conclusion for the effect of a linear sloping interface on the phase velocity of Rayleigh waves was made earlier by Kuo and Nafe (1962)[1], and Kuo and Thompson (1964)[2]. Furthermore,

[1] Kuo, J. and J. Nafe, Period equation of Rayleigh waves in a layer overlying a half space with a sinusoidal interface, Bull. Seism. Soc. Am., 52, 807-822, 1962.

[2] Kuo, J. and G. Thompson, Model studies on effect of a sloping interface on Rayleigh waves, J. Geophys. Res., 68, 6187-6197, 1964.

Takahashi has found that the condition for transmission and backward reflection critically depends upon the wave leng. of the incident wave and the thickness variation of the layer. He has extended his investigation to the asymmetrical problem by replacing the half of the hyperbolic layer with a parallel layer and the half space is assumed to be rigid. There is assumed no first-order discontinuity at the junction of the hyperbolic layer and the parallel layer. Under these prescribed conditions, the wave function of Love waves, even in the region of the parallel layer, was found to be a composite of an infinite number of modes, whereas for the case of a parallel layer, the wave function is generally treated as separate modes.

During the past ten years, Miss Lehmann (now Doctor Lehmann - she received an honorary Ph. D. from Columbia in 1964) has been a frequent visitor to Lamont. Her scientific achievements and interest in seismology have added a great deal of strength to this project. She not only has served as a consultant to the seismology group but also has carried out several research projects which bear immediate relation the wave propagation generated by explosions and earthquakes.

Some interesting results on the travel times of P in North America as determined from nuclear explosions are obtained by Dr. Lehmann. Fourteen reports of nuclear shots at the NTS are used in her study. Mean travel times of P to individual stations are determined and found to have considerable accuracy for distances less than 500 km. For greater distances, they often have deviations concentrated on two values about one second apart.

The travel times of P for the profiles of stations centered at the NTS are compared with $t(P) = 8.3 + 1/8.02\Delta$ for distances up to 1800 km. The residuals against t(P) for the ESE profile, which passes near the Gnome site, are small up to about 700 km, but for greater distances they are mostly about 2 to 3 seconds. Dr. Lehmann concludes that this deviation indicates the presence of a disturbance at some depth, possibly a low velocity layer.

To the NE of the Gnome site, the P travel times are known to be increasingly early. The profile extending E from the NTS has some stations close to, or in common with the Gnome profile, but the P travel times at these stations are not early. She feels that the high-speed layer responsible for the early Gnome times seems to be of small extent.

In her further study on the travel times of P in North America as determined from both nuclear explosions and earthquakes, Dr. Lehmann found that (1) some California stations at distances around 1700 km observed that P of the Gnome shot has an exceptional delay of 4 1/2 seconds; (2) the New Madrid earthquake of February 2, 1962, had its epicenter on the Gnome northeast line, but the surface velocity of Pn for the earthquake is smaller on the line than that of the Gnome shot. Pn of the earthquake was well recorded in all directions from the epicenter; there is no evidence for a low-velocity layer at small depth in these regions. It seems that the shallow low-velocity layers are confined to the western mountain regions.

An excellent study of the deep Hindu Kush earthquake of March 4, 1949, from distances 36°-50° was made by Dr. Lehmann. The many, clearly recorded deep-focus reflections lend to the records a characteristic appearance, which is repeated in many other shocks from the same focal regions. Most of these 1949 records were from the old type, long period instruments having their highest magnification for periods from about 5 sec to 12 sec. Unfortunately, present day instruments of either quite short or of very long proper period, while admirable for many purposes, do not record waves in this period range very well and therefore do not produce a satisfactory picture of the forerunners of earthquakes. Her remarks should be seriously considered in terms of future seismological development. It may be advisable to cover as wide a frequency spectrum as possible in order to record such phases.

Dr. Nakagawa of the Kyoto University has contributed additional knowledge to the free oscillation data from the great Chilean earthquake of May 22, 1960 recorded on a gravimeter at Brussels. The peak corresponding to fundamental modes within the periods from 60 minutes to 4 minutes are in good

agreement with those theoretically calculated except that a few peaks are missing. The first and second overtones for several modes are also observed. Evaluation of the screening effect on the M_1 component was also attempted by Nakagawa, although the results were not conclusive.

During a short period of stay, Drs. Y. Satô, T. Usami and H. Takeuchi of the Earthquake Research Institute, Tokyo University, accomplished a great deal of numerical computation in their investigations on inversion and density problems on an IBM 7094. Additionally, Dr. Takeuchi has succeeded in deriving analytical expressions for partial derivatives of surface wave phase velocity by means of energy equations, which are equivalent to fundamental equations and boundary conditions in surface wave problems. The partial derivatives are expressed in terms of physical parameter changes within the earth and can be calculated by knowing only the eigen function corresponding to the phase velocity. This approach simplifies Dorman's previous work on the numerical inversion problem of surface waves.

Dr. R. Sato of the Geophysical Institute of Tokyo University was with us for nearly two years and has made considerable progress in his determination of the dissipation factor Q distribution within the earth. He has extended the earth model with no sharp discontinuities, investigated earlier, to a model which includes a crustal layer. An equation for determination of Q distribution with depth in the mantle by using the observed Q values for Love waves was derived. Observed values of Q for Love waves show a decrease with increasing period in the period range from 100 to 400 seconds. When Q for shear waves in the crust is larger than Q in the mantle, Q for Love waves decreases with period in the above-mentioned period range even when Q in the mantle increases with depth. This suggests that the value of Q in the upper mantle may be smaller than that in the crust. If Q were almost constant in a wide range of the upper mantle, Q in the crust might be several times the Q in the mantle.

By using the phases ScS, sScS, and their multiples, he has found that the mean value of Q in the mantle is about 200. Furthermore, he has

investigated the effect of a soft-solid core and a viscous-fluid core upon the fundamental mode of torsional free oscillations of the earth.

We were very fortunate to have Sir Harold Jeffreys with us. During his stay at Lamont, Sir Harold worked primarily on a revision of the travel times from Japanese earthquakes. His previous work on this subject utilized data from shallow earthquakes. In order to improve the travel time curves, his present study used only data from deep-focus earthquakes. A student from Cambridge, who accompanied Sir Harold, will use part of these results in his thesis. In addition, Sir Harold wrote a short note on Fourier analysis of seismograms which helped to resolve some of the difficulties involved in the interpretation of free oscillation data.

FUTURE OUTLOOK

We gratefully acknowledge renewal of this project by the Air Force Office of Scientific Research, under Grant No. AF-AFOSR-887-65, beginning September 1, 1965, for a period of two years. It appears certain that much valuable exchange of scientific knowledge and experience in the field of seismology between the visiting seismologists and our staff will be as fruitful in the future as it has been in the past. It is self-evident that careful selection of visiting seismologists is the key to the success of the project; we will be continuously guided by this principle.

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